Constraints on Large-Extra-Dimensions model through 125GeV Higgs pair production at the LHC

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Based on the analysis of 5 fb^{-1} of data at the LHC, the ATLAS and CMS collaborations have presented evidence for a Higgs boson with a mass in the 125 GeV range. We consider the 125 GeV neutral Higgs pair production process in the context of large-extra-dimensions(LED) model including the Kaluza-Klein(KK) excited gravitons at the LHC. We consider the standard model(SM) Higgs pair production in gluon-gluon fusion channel and pure LED effects through graviton exchange as well as their interferences. It is shown that such interferences should be included, the LED model raises the transverse momentum(P_t) and invariant mass(M_{HH}) distributions at high scales of P_t and M_{HH} of the Higgs pair production. By using the Higgs pair production we could set the discovery limit on the cutoff scale M_S up to 6 TeV for $\delta = 2$ and 4.5 TeV for $\delta = 6$.

Gravitation is by far the weakest force of nature with the usual explanation that quantum gravitational effect only become important at the Planck mass scale $M_{pl} = G_N^{-1/2} = 1.22 \times 10^{19}$ GeV. The fact that this scale is so much higher than the SM electroweak scale of $O(100$ GeV $)$ leads to the hierarchy problem. Arkani-Hamed, Dimopoulos, and Dvali (ADD)[1][2] proposed that extra spatial dimensions could potentially solve such problem in the SM[3]. They proposed a scenario in which the SM is constrained to the common 3+1 space-time dimensions (brane), while gravity is free to propagate throughout a larger multidimensional space (bulk). The gravitational flux on the brane is therefore diluted by virtue of Gauss's Law in the bulk, which relates the fundamental Planck scale M_S to the apparent reduced scale according to the formula $M_{pl}^2 = 8\pi M_S^{\delta+2} R^\delta$, where R and δ are the size and number of the extra dimensions(ED), respectively. Postulating a fundamental Planck scale to be on the order of the electroweak symmetry breaking scale (1 TeV) results in ED with $R < 1$ mm for $\delta \geqslant 2$.

At hadron colliders, the pair production of Higgs bosons plays a distinctive role in understanding the Higgs mechanism[4]. As the triple self-coupling of Higgs particles is involved in such production thus provide the experimental reconstruction of the Higgs potential. Precise measurement of this coupling could therefore give more insight on the mechanism of electroweak symmetry breaking. Further more, compared to that of a single Higgs boson production, the signal-to-background ratio could significantly improved. The invariant mass scale of the single Higgs production is fixed by the Higgs mass, of order only ~ 100 GeV. Thus

their detection through heavy quark decay modes suffer from large QCD backgrounds. Besides, one viable decay mode $h \to \gamma\gamma$ has a very small branching ratio of order 10^{-3}[5]. While for the pair production of the Higgs particles, the four b-jets in the final states are energetic and reduce main background coming from $Hb\bar{b}$ with soft b-jets[6], thus provide better signal-to-background ratio.

Another important distinctive feature of the Higgs pair production at the LHC is that the effects of physics beyond the SM can remarkably enhance the cross section with respect to that of the SM. Phenomenological studies of Higgs pair production have thus been performed in the context of the 4th generation model[7], the littlest higgs model[8] and the Universal Extra Dimensions model[9]. For the large extra dimensional models, the tree level diagrams mediated by the Kaluza-Klein gravitons lead to a large total cross section. Such new theoretical approaches have drawn extensive attention in ref[10] for a comparantion between supersymmetry and LED models. In the context of the large-extra-dimensions(LED) model, lower limits are set on the effective Planck scale in the range of 2.3~3.8 TeV at the 95% confidence level[11]. These limits are the most restrictive bounds on virtual graviton exchange to date. Based on the analysis of 5 fb^{-1} of data at the LHC, the ATLAS[12] and CMS[13] collaborations have presented evidence for a Higgs boson with a mass in the 125 GeV range. We thus concentrate on the 125 GeV Higgs pair production related to the latest measurement with the effects of the LED models and find the characteristic distribution of it and give the observable and unobservable limits of the effective
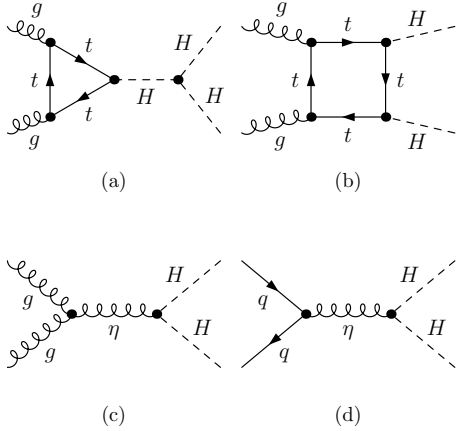
Planck scale theoretically.

FIG. 1: Part of Feynman diagrams for $pp \to HH$ in the SM and LED, where q represents u-,d-,c-,s-, and b-quark while η represents spin-2 KK graviton.

In FIG.1 we display the Feynman diagrams for this rare production $pp \to HH$ at the LHC in both the SM and LED model. There is gluon-gluon fusion channel contribute to SM predictions through top-quark loops, see FIG.1(a,b) for more details. There is also b-quark contribution, but it is small. Other diagrams include the change of the loop arrow in FIG.1(a,b) and cross change of the legs in FIG.1(b) which are similar thus not shown, totally eight Feynman diagrams contribute. Contributions from the quark-antiquark collision can be safely omitted in the light fermion mass limits except b-b fusion through t-channels. However, it is only less of 0.5 percent of gluon-gluon fusion contribution, thus not considered here[7]. Now let's study the effects of KK excitation of gravitons on the production cross section of $pp \to HH$. There exist tree level Feynman diagrams mediated by KK-gravitons(η) only in s-channel: the gluon-gluon fusion(FIG.1 (c)) and quark-antiquark collision(FIG.1 (d)). Furthermore, gravitons with polarizations that lie entirely within the physical dimensions are effective spin 2 objects. So we will primarily be concerned with the effects of the exchange of virtual spin 2 gravitons. To perform perturbative calculations in this theory, one can formulate Feynman rules for the couplings of graviton states to ordinary particles. Related couplings in FIG.1(c,d) can be found in ref.[14, 15]. Such couplings would proportional to $\kappa = \sqrt{16\pi G_N}$ which is the effective expansion parameter. In particular, we adopt the conventions of ref.[15]. We define the SM cross section as σ_{SM} and use σ_{LED} to perform pure LED cross section plus the interfer-

ence between SM and LED effects. σ_{tot} is defined as $\sigma_{SM} + \sigma_{LED}$.

In the case of the exchange of virtual graviton states, one must add coherently the effect of each graviton. For instance, in our case of only s-channel exchange, the propagator is proportional to $i/(s - M_\eta^2)$ where M_η is the mass of the graviton state η. Thus, when the effects of all the gravitons are taken together, the amplitude is proportional to $\sum_\Lambda \frac{i}{s - M_\eta^2} = D(s)$. If $\delta \geq 2$ this sum is formally divergent as M_η becomes large. We assume that the distribution has a cutoff at $\Lambda \sim M_S$, where the underlying theory becomes manifest. After summing over all KK states, the effective graviton propagator $D(s)$ times square of the coupling κ can be expressed as

$$\kappa^2 D_s = \frac{8\pi}{M_S^4}(\frac{\sqrt{s}}{M_S})^{\delta-2}[\pi + 2iI(\Lambda/\sqrt{s})]. \qquad (1)$$

The function $I(\Lambda/\sqrt{s})$ depends on the ultraviolet cutoff Λ on the KK modes and its expression can be found in ref.[15]. The default choice for Λ would be the fundamental scale M_s.

We use FeynArts, FormCalc and LoopTools package[16–18] to perform the numerical calculation. We use BASES[19] to perform the phase space integration and cern libary to display the distributions. In the numerical calculations, we take the input as $M_Z = 91.1876$ GeV, $M_W = 80.399$ GeV, $\alpha(0)^{-1} = 1/137.035999779$[20]. The factorization scale is chosen to be $\mu = M_H = 125$ GeV at 14 TeV LHC with the luminosity $\mathcal{L}$ as a running parameter. Typically the latest new parton distributions for collider physics CT10[21] has been used in our calculation.
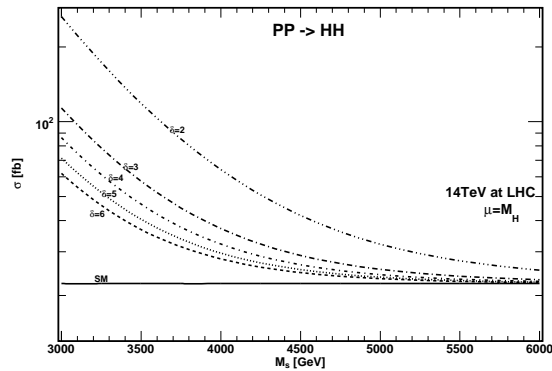

FIG. 2: The cross sections for the process $pp \to HH$ in the SM and LED model as functions of M_S with $\mu = M_H$ and $\delta = 2, 3, 4, 5, 6$ at the $\sqrt{s} = 14 TeV LHC$.
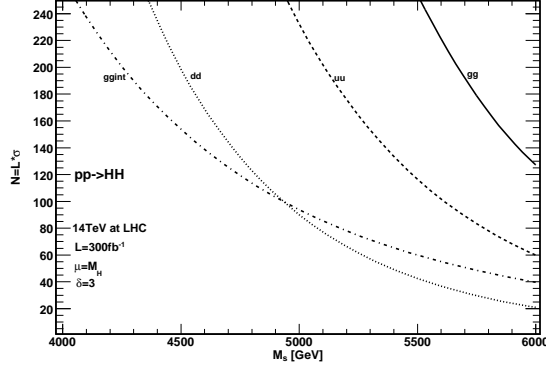
FIG. 3: The expected number of events produced of separate contributions of LED effects for $pp \rightarrow HH$ with $M_s = 3TeV$, $\mu = M_H = 125GeV$ and $\delta = 3$ at 14 TeV LHC . The luminosity is taken as $\mathcal{L} = 300fb^{-1}$. Here, gg, uu, dd and ggint present the gluon-gluon fusion, up-quark collision, down-quark collision and interference contributions.

In FIG.2, we depict the cross sections for the process $pp \rightarrow HH$ at 14 TeV LHC in the LED model as the functions of the fundamental scale M_S from 3 TeV to 6 TeV, with $\mu = M_H$ and the extra dimension number δ being 2,3,4,5 and 6, respectively. The solid line presents the SM prediction σ_{SM} and the other lines correspond to $\sigma_{tot} = \sigma_{SM} + \sigma_{LED}$. From the figures one finds that the largest deviation from the SM due to LED occurs at small values of M_S and δ. In order to compare the relative size of different subcontributions, we display in FIG.3, the expected number of events($\mathcal{N} = \mathcal{L} \cdot \sigma$) for each sub-contribution to Higgs pair production for $\delta = 3$, $\mu = M_H$ and the luminosity $\mathcal{L} = 300fb^{-1}$. The terms gg, uu, dd, ggint refer to pure gluon-gluon fusion, $u\bar{u}$, $d\bar{d}$ collisions and to the gluon-gluon interference term respectively. As can be seen, as the scale M_S becomes larger, all subcontributions turn out to be of the same order. Moreover, the gluon-gluon interference term can be even lager than the down-quark contribution when M_S is larger than 4.9 TeV. Thus all these contributions should be included for a precise prediction.

The distributions of the Higgs pair invariance mass M_{HH} and the Higgs boson transverse momentum P_t as well as the rapidity η at 14 TeV LHC, are shown in Fig.4 (a), (b) and (c), separately. There the results are for $M_s = 3$ TeV, $\mu = M_H = 125$ GeV at the fixed value 3 for the number of extra dimensions and obtained by taking the input parameters mentioned above. In FIG.4 (a), (b), the SM and LED invariance mass peaks around the threshold $\sqrt{s} = 250$ GeV while P_t
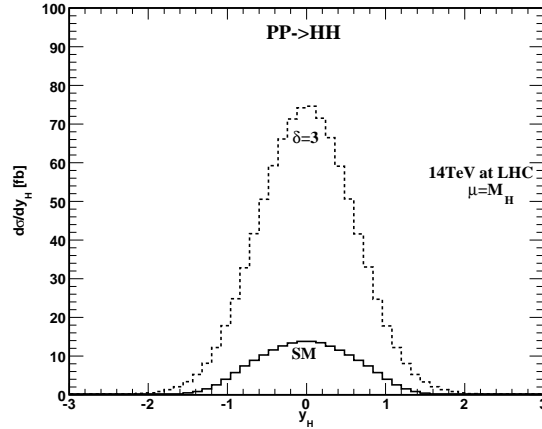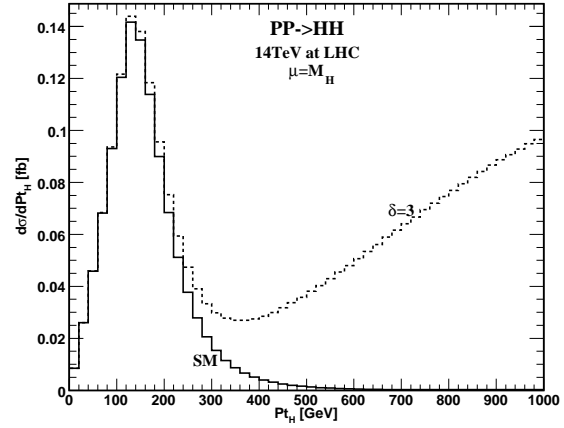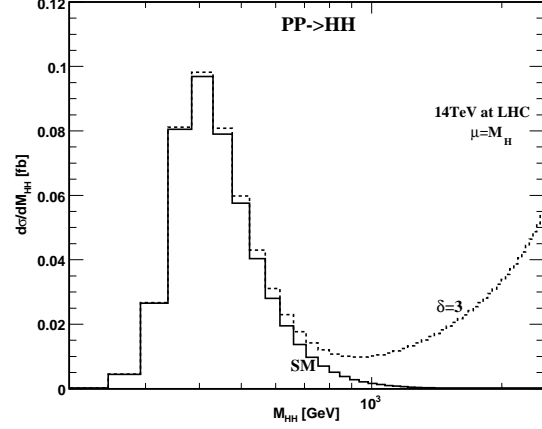

FIG. 4: The invariance mass M_{HH}, transverse momentum P_t and rapidity η distribution with $M_s = 3TeV$, $\mu = M_H = 125GeV$ and $\delta = 3$ at 14 TeV LHC for $pp \rightarrow HH$. The first, second and third figure correspond to (a),(b) and (c), separately.

distribution peaks around 150 GeV. The LED effects gently raise the M_{HH} and P_t distributions at values of high M_{HH} and P_t regions. Rapidity distribution is defined as $\frac{d\sigma}{d\eta}$ with $\eta = \frac{1}{2}\ln(P_1 \cdot q)/(P_2 \cdot q)$, where P_1 and P_2 are incoming proton momenta and q is the sum of the Higgs boson 4-momenta. As we can see, the rapidity distributions in the LED model show significantly narrow peaks around $\eta = 0$, which implies the large contributions at high P_t region.

It is clear that if the deviation of the cross section from the SM prediction is large enough, the LED effects can be found. We assume that the LED effects can and cannot be observed, only if[22]

$$|\sigma_{LED}| \geq \frac{5\sqrt{\mathcal{L}\sigma_{tot}}}{\mathcal{L}} \equiv 5\sigma \qquad (2)$$

and

$$|\sigma_{LED}| \leq \frac{3\sqrt{\mathcal{L}\sigma_{tot}}}{\mathcal{L}} \equiv 3\sigma \qquad (3)$$

,respectively. In TABLE.1, we present the discovery and exclusion fundamental scale M_S values at the 14 TeV LHC with the luminosity $100fb^{-1}$, $200fb^{-1}$ and $300fb^{-1}$. It shows that by using the Higgs pair production we could set the discovery limit on the cutoff scale M_S up to about 6 TeV for $\delta = 2$ and 4.3 TeV for $\delta = 6$ with the luminosity $\mathcal{L} = 300fb^{-1}$ at the LHC. Other similar analysis of pair productions that probe the LED model through virtual effects of KK modes have been studied in processes like di-lepton, di-gauge boson($\gamma\gamma$, ZZ, W^+W^-), $t\bar{t}$ pair, dijet[23–26] etc. At LHC, it is expected that $t\bar{t}$ production can be used to explore a range of M_S values up to 4 TeV. Through di-photon production the LHC can extend this search to 5.3-6.7 TeV, depending on the number of extra dimensions. While using di-lepton production, a lower bound of M_S in the 6.5 to 12.8 TeV range can be obtained. The phenomenology of the Higgs pair production is at the time much richer[27], though Higgs pair production cannot give compete limits as, for example, di-lepton production gives, it's still very important.

In a short summary, we calculate the $pp \rightarrow HH$ process in the SM and LED model at the 14 TeV LHC with the 125 GeV mass Higgs pair production. We keep all the contributions include gluon-gluon fusion, quark-antiquark collisions as well as gluon-gluon fusion interference terms between SM and LED. We investigate the integrated cross sections, the distributions of some kinematic variables M_{HH}, P_t and η. The 5σ discovery and 3σ exclusion ranges for the LED parameters M_S are also obtained. The effects of the virtual

$\mathcal{L}$	$100fb^{-1}$		$200fb^{-1}$		$300fb^{-1}$	
	5σ	3σ	5σ	3σ	5σ	3σ
$\delta = 2$	5396	6121	5720	6488	5917	6699
$\delta = 3$	4568	5128	4824	5405	4978	5551
$\delta = 4$	4294	4810	4528	5046	4666	5193
$\delta = 5$	4113	4612	4333	4822	4469	4962
$\delta = 6$	3983	4458	4199	4674	4312	4789

TABLE I: The discovery ($|\sigma_{LED}| \geq 5\sigma$) and exclusion ($|\sigma_{LED}| \leq 3\sigma$) LED model fundamental scale (M_S) values for the $pp \rightarrow HH$ processes at the $\sqrt{s} = 14$ TeV LHC.

KK graviton turns out to enhance the differential distributions of kinematical observables generally. With the observable of 125 GeV Higgs boson production, more information related to LED effects can be obtained experimentally through such important production.

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